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Potential Cost Savings for Use of 3D Printing Combined With 3D Imaging and CPLM for Fleet Maintenance and Revitalization

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Panel 19. Toward Cost Reductions in Ship Design and Maintenance

Thursday, May 15, 2014	
1:45 p.m. – 3:15 p.m.	**Chair: RADM David Lewis,** USN Program Executive Officer, SHIPS ***Potential Cost Savings for Use of 3D Printing Combined With 3D Imaging and CPLM for Fleet Maintenance and Revitalization*** David Ford, Texas A&M University Tom Housel, Naval Postgraduate School ***A Proposal for Reducing Work Content in Early Stage Naval Ship Design*** Robert Keane, Ship Design USA Inc. Laury Deschamps, SPAR Associates, Inc. Steve Maguire, First Marine International ***Does Computer Based Training Impact Maintenance Costs and Actions? An Empirical Analysis of the U.S. Navy's AN/SQQ-89(v) Sonar System*** Robert McNab, Naval Postgraduate School Diana Angelis, Naval Postgraduate School

Potential Cost Savings for Use of 3D Printing Combined With 3D Imaging and CPLM for Fleet Maintenance and Revitalization

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Abstract

Initiatives to reduce the cost of ship maintenance have not yet realized the normal cost-reduction learning curve improvements. One explanation is the lack of effective and efficient technologies. Two such recommended technologies are collaborative product lifecycle management (CPLM) and three-dimensional laser-scanning technology (3DLST). One quickly emerging new technology is additive manufacturing (AM). The research team collected data on AM use by the U.S. Navy in maintenance operations and used them to build two types of computer simulation models of ship maintenance and technology adoption. The models were used to investigate the impacts of CPLM and 3DLST and scaling up AM use on potential cost savings. Results were analyzed and compared with previous model results of the use of AM in U.S. Navy ship maintenance. Results support the adoption of AM in ship maintenance. 3DLST increases savings slightly over using AM alone or with CPLM. Cost savings when AM is used only to make prototypes are significant but limited. In contrast, savings are larger if AM is used to manufacture final parts. The primary implication for acquisition practice is the importance of scaling up the use of AM and other new technologies to capture potential savings.

Introduction

The current cost-constrained environment within the federal government and the Department of Defense (DoD) requires a defensible approach to cost reductions without compromising the capability of core defense processes and platforms. Due to this environment, defense leaders today must maintain and modernize the U.S. armed forces to retain technological superiority while simultaneously balancing defense budget cost constraints and extensive military operational commitments. At the same time, defense leaders must navigate a complex information technology (IT) acquisition process. Maintenance programs play a critical role in meeting these DoD objectives. One such core process that is central to U.S. naval operations is the ship maintenance process. This process alone accounts for billions of dollars in the U.S. Navy's annual budget. There have been a series of initiatives designed to reduce the cost of this core process, including ship maintenance.

SHIPMAIN, and its latest derivatives, was one of the initiatives designed to improve ship maintenance performance within the Navy by standardizing processes in order to take advantage of learning-curve cost savings. However, these process improvement initiatives have not yet realized the normal cost-reduction learning-curve improvements for common maintenance items for a series of common platform ships. One explanation is that the initial instantiation of SHIPMAIN did not include the requisite technologies. Two of these technologies, three-dimensional laser-scanning technology (3DLST) and collaborative product lifecycle management (CPLM), were deemed necessary by the creator of SHIPMAIN for ensuring the success of the new standardized approach (i.e., normal learning-curve cost savings). A third technology, additive manufacturing (AM), has developed quickly over recent years and shows potential in generating even greater cost savings if combined with the other two technologies.

These technologies have not been widely implemented for ship maintenance across the Navy. One explanation is that the combination of the three technologies, unless scaled up, will not provide adequate cost savings. The combination of these three technologies at different operational scales will significantly affect savings when compared to their application alone, in pairs, or at inefficient scales of operation. An improved understanding of the cost impacts of the adoption of all three technologies at different scales of adoption can facilitate Navy decision-making about the possible acquisition and use of these technologies. The current work estimates the cost reduction impacts of adopting AM, CPLM, and 3DLST for ship maintenance at different scales of operation.

Problem Description

AM + CPLM + 3DLST have demonstrated the capacity for improving military operations, such as Navy ship maintenance. The U.S. Army has successfully deployed three “expeditionary labs” to Afghanistan. These self-contained spaces use AM, as well as computer numerical control (CNC) machines, to quickly reequip the Army’s Rapid Equipping Force (Chayka, 2013). The Navy has initiated testing of AM at the Navy Warfare Development Command and limited use at Naval Air Systems Command (NAVAIR) in San Diego and Fleet Readiness Center Southwest at Port Hueneme. Industry leaders, such as Boeing and General Electric (GE), currently use AM to create final parts for machines and vehicles. But current U.S. military certification processes prevent them from using these methods for military components (Chayka, 2013). Damen, the primary naval contractor for the Dutch navy, has successfully adopted and is currently using core components of CPLM (Ford, Housel, & Mun, 2012), and two U.S. navy shipyards have begun the transition to CPLM for shipbuilding.

Previous related research has investigated the cost/benefits impacts of the U.S. Navy using 3DLST and CPLM (Komoroski, 2005), CPLM and 3DLST (Ford et al., 2012) and AM and CLPM in ship maintenance (Kenney, 2013). Ford et al. (2012) modeled the cost/benefits impacts of CPLM and 3DLST ship maintenance operations. Kenney (2013) modeled two levels of AM adoption: use only for making prototypes; and use for both prototypes and final parts, referring to these as “immature” and “mature” AM, respectively. All of these studies predicted that significant cost reductions can be captured through the use of these new technologies. Although adoption and ramp-up costs and other issues (e.g., contracting regulations) are not included in these cost/benefits impact studies, the scale of potential savings is so large (exceeding $1 billion in some cases) that projected cost savings appear to have been adequate for adoption of the technologies. Tests of the combined use of the three technologies at different levels of use for cost savings impacts may facilitate naval decision-making and progress. Therefore, the current work addresses the following questions:

- How does the use of 3DLST impact the returns on investment and cost savings that can be expected from the use of AM and CPLM alone for ship maintenance?
- What returns on investment and cost savings can be expected from the use of AM, CPLM, and 3DLST in combination for rapid prototyping in ship maintenance?
- What returns on investment and cost savings can be expected from the use of AM, CPLM, and 3DLST for rapid prototyping and final parts manufacturing in ship maintenance?

Background

Collaborative Product Lifecycle Management

CPLM technology provides a common platform to electronically integrate other technologies, such as 3DLST images and manufacturing files for AM, to enable collaboration among all parties involved in a given project across project phases and regardless of their geographic location (e.g., on a ship at sea and at a land-based depot). CPLM tools also provide a means to store the images and all related maintenance work within a common database accessible by all participants in a ship alternation or modernization project. PLM integrates people, processes, and information. More specific CPLM tools include technologies that support data exchange, portfolio management, digital manufacturing, enterprise application integration, and workflow automation. A range of industries have invested in CPLM solutions, including those involved in aerospace and defense, automotive and transportation, utilities, process manufacturing, and high-tech development and manufacturing. The CPLM market is poised for further growth with vendors expanding product offerings as the industry evolves.[1]

Three-Dimensional Laser-Scanning Technology

3D scanners create a “point cloud” of the surface of an object. 3D scanners are similar to cameras in some ways. They have a cone-shaped field of view. But 3D scanners can also collect distance information about each point, allowing each point to be located in a three-dimensional space. Usually, multiple scans are required from different directions to capture adequate information to create a description of the object. Most manufacturers’ scanners work by scanning a target space with a laser light mounted on a highly articulating mount, enabling data capture in virtually any orientation with minimal operator input. Some also incorporate a digital camera that simultaneously captures a 360° field-of-view color photo image of the target. Once the capture phase is complete, the system automatically executes proprietary point-processing algorithms to process the captured image. The system can generate an accurate digital 3D model of the target space, automatically fuse image texture onto 3D model geometry, export file formats ready for commercial, high-end design, and import them into 2D/3D computer-aided design (CAD) packages.

[1] The two largest U.S. shipyards that construct aircraft carriers and submarines are also transitioning into collab-PLM solutions. Typically, PLM vendors do not focus efforts on the shipbuilding industry because of its size relative to other products, such as automotive or aerospace. Having a PLM tool designed specifically for an industry has a significant impact on the tools efficiency within that industry.

3D laser-scanning technology is well established as a useful tool in practice and is currently used in a variety of industries. According to industry analysts, laser-scanner manufacturers and related software and service providers report strong activity across many markets, including shipbuilding, offshore construction and repair, onshore oil and gas, fossil and nuclear power, civil and transportation infrastructure, building, automotive and construction equipment, manufacturing, and forensics (Greaves & Jenkins, 2007). In the latest data available, sales of terrestrial 3D laser-scanning hardware, software, and services reached $253 million in 2006—a growth of 43% over 2005 (Greaves & Jenkins, 2007).

Additive Manufacturing

Additive manufacturing (AM) is the youngest and most diverse technology addressed in this research. AM is defined by the American National Standards Institute (ASTM, 2013) as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (Wohlers Associates, 2010). AM is a state-of-the-art manufacturing methodology, which has radical differences with the currently dominant manufacturing methodologies (Gibson, Rosen, & Stucker, 2010; Lipson & Kurman, 2013). Although most current methods use subtractive processes (e.g., machining), AM builds a 3D object by gradually adding successive layers of material that are laid down exactly in the final location they should be. The basic principle of the AM process is to fabricate an object directly from a three-dimensional computer-aided design (3D CAD) model. During the manufacturing process, the 3D model is disaggregated into multiple layers, each of which is produced by the machine and added to the preceding layers. Integration of all layers forms the final 3D object.

AM provides several advantages over traditional manufacturing processes. AM minimizes intermediate steps and streamlines manufacturing processes. AM provides the opportunity to make a product in one part, regardless of the number of its components and complexity of their connections. One of the advantages of AM is the freedom it provides for designers. This is the result of layer-by-layer fabrication. Any geometric form is broken into very thin layers, which are produced and connected successively. The more complexity, the more advantage can be gained by using AM. Another advantage of AM is its accuracy. AM processes can operate with resolution of a few tens of microns, as tiny as diameter of human hair.

However, AM also has limitations. A primary limitation concerns the materials that can be used in AM. AM technologies were originally developed around polymer materials. Then some other materials, such as metals, were introduced. But the current approach remains limited to a range of materials and their physical properties (e.g., strength). Some of the AM methods can use only one or a few materials. Some AM materials require careful handling. They usually have a limited shelf life and must be kept in conditions that prevent them from unwanted chemical reactions. Exposure to moisture, excessive light, and so forth may degrade or destroy some materials. Another problem is that, although most of the AM materials can be used several times theoretically, in practice reuse can degrade their properties over time.

AM has quickly moved through technology development into the mainstream, with web pages now offering services that allow the public to design and use AM to produce products of their choosing (e.g., see Kronsberg, 2013).

Research Methodology

The research team collected data on the use of AM by the Navy and used it and information from the literature to build two types of computer simulation models of ship

maintenance: a system dynamics (SD) model of ship maintenance operations, and knowledge value added (KVA) models of return on technology investments. The models were used to simulate six scenarios that represent realistic conditions of the use of the technologies. The results were then used to estimate cost savings for each scenario if they were applied to routine ship maintenance processes more generally. This extrapolation from the actual experience with AM at the NAVAIR maintenance depot to wider use is supported by the similarity in the processes and kinds of legacy repair and replacement parts that are most prevalent in routine ship maintenance. The results from this modeling were then compared with previously developed modeling results of U.S. Navy ship maintenance and technology adoption. In this section, we review the two approaches, beginning with a general review of the KVA and SD approaches. This is followed in a description of the data collection and the models in the next section and the projected results from applying these approaches. A comparison of the results with previous results and discussion follows.

Knowledge Value Added

KVA measures the value provided by human capital and IT assets by an organization, process, or function at the subprocess level. It monetizes the outputs of all assets, including intangible knowledge assets. Capturing the value embedded in an organization's core processes, employees, and IT enables the actual cost and revenue of a product or service to be calculated. In KVA total value is captured in two key metrics: return on investment (ROI) and return on knowledge (ROK; see Table 1). Although ROI is the traditional financial ratio, ROK identifies how a specific process converts existing knowledge into producing outputs so decision-makers can quantify costs and measure value derived from investments in human capital assets. A higher ROK signifies better utilization of knowledge assets. If IT investments do not improve the ROK value of a given process, steps must be taken to improve that process's function and performance.

The goal is to determine which core processes provide the highest ROIs and ROKs, and to make suggested process improvements based on the results. In the current work, KVA is used to measure the benefits of technology adoption in ship maintenance. This analysis provides a means to check the reliability of prior studies' estimates of the potential ROI core process improvements from using CPLM, AM, and 3DLST in ship-maintenance core processes in the U.S. Navy yards.

System Dynamics

The system dynamics methodology applies a control theory perspective to the design and management of complex human systems. System dynamics combines servo-mechanism thinking with computer simulation to analyze systems. It is one of several established and successful approaches to systems analysis and design (Flood & Jackson, 1991; Jackson, 2003; Lane & Jackson, 1995). Forrester (1961) developed the methodology's philosophy, and Sterman (2000) specified the modeling process with examples and applications. The system dynamics perspective focuses on how the internal structure of a system impacts system and managerial behavior and, thereby, performance over time. The approach is unique in its integrated use of stocks and flows, causal feedback, and time delays to model and explain processes, resources, information, and management policies. Stocks represent accumulations or backlogs of work, people, information, or other portions of the system that change over time. Flows represent the movement of those commodities into, between, and out of stocks. The methodology's ability to model many diverse system components (e.g., work, people, money, value), processes (e.g., design, technology development, production, operations, quality assurance), and managerial decision-making and actions (e.g., forecasting and resource allocation) makes system

dynamics useful for modeling and investigating military operations, such naval ship maintenance, the focus of the current study.

The system dynamics methodology provides several advantages in simulating complex dynamic systems, such as the use of advanced technologies for naval ship maintenance. First, system dynamics models make causal feedback explicit. Feedback can be critical in understanding, explaining, and exploiting the structure of dynamic systems. An example of feedback in the current work is the return of prototypes to design after they fail the inspection or functional tests. Other features of system dynamics models can be used in the future to improve the understanding of the drivers of behavior and performance, including the ability to simulate related activities and costs (e.g., materials savings and manufacturing infrastructure) and the ability to simulate transitions from one steady state to another, such as from current levels of adoption to full adoption.

Data Collection and System Description

One member of the research team (Housel) and a graduate student (Kenney) visited the Naval Surface Warfare Center Port Hueneme Division (NSWC PHD) on May 10, 2013, and collected detailed information on the use of AM by that facility. They then visited the Naval Air maintenance depot in San Diego on July 17 and 18, 2013, and interviewed Gabe Draguicevich of the Fleet Readiness Center Southwest concerning the use of AM at the North Island NAVAIR maintenance depot. Based on that data and a review of the literature, Kenney (2013) developed a description of the current processes based on the collected information, summarized next.

The parts maintenance process includes both administrative and manufacturing-related processes. The manufacturing related processes include both information processing and processes performed on the materials that eventually become the part itself. Although the system includes a number of important iterative loops (described later), the processes are generally sequential. The process as initially depicted by Kenney (2013) does not include feedback. However, Kenney (2013) partially described the feedback with the iteration in the depot-level machining shop process (see Figure 1).

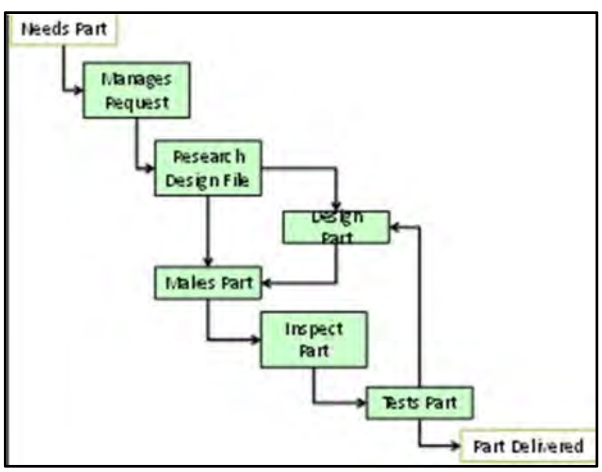

Figure 1. Depot-Level Machining Shop Process
(Kenney, 2013)

In addition to the feedback shown in Figure 1, a feedback loop exists when parts fail inspection. In this feedback loop, parts move from “Inspect Part” to “Design Part,” then to “Makes Part,” and back to “Inspect Part” again. These two feedback loops are shown in the

causal loop diagram[2] in Figure 2, which includes the processes diagrammed by Kenney (2013) in Figure 1 and the similar variables used in the system dynamics model in parentheses. Figure 2 shows the reinforcing feedback loop R1, the failed testing loop described in Figure 1, and the reinforcing feedback loop R2, the failed inspection loop that is created by adding the causal link (heavy arrow) from “Inspect part (Inspection rate)” to “Design part (Complete DAC design rate).” Figure 2 also indicates the roles of the process of gathering existing conditions, which the 3DLST facilitates, and the inspection and testing failure fractions, which determine the volume of work caught in the rework cycle. These processes and feedback were incorporated into the formal system dynamics model. They thereby impact the KVA model results and the performance metrics of different technology adoption and use strategies.

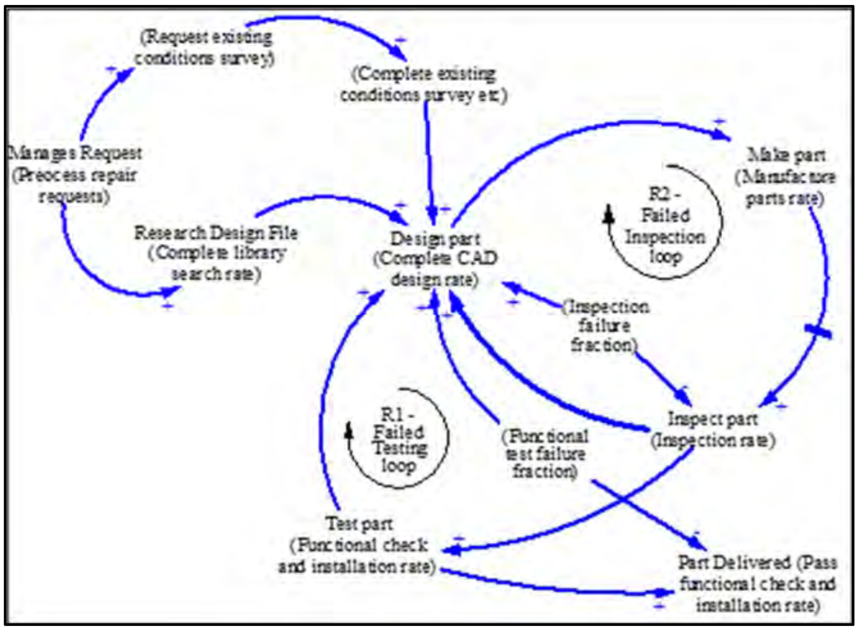

Figure 2. Partial Feedback Model of the Repair Part Manufacturing Processes

Note. Legend of Loops:

R1—Failed Testing loop: More part testing increases designing parts, which increases making parts, inspecting parts, and thereby the testing of parts.

R2—Failed Inspection loop: More part inspections increases designing parts, which increases making parts and thereby inspecting parts.

[2] Causal loop diagrams are used in system dynamics to conceptually model feedback in systems. In causal loop diagrams, arrows indicate the direction of causality. Signs indicate the polarity of relationships. A “+” sign means that, ceteris paribus, an increase (decrease) in a variable causes an increase (decrease) in its impacted variables; and a “-” sign means that an increase (decrease) causes an decrease (increase) in its impacted variables. Loops are labelled “R” for “reinforcing,” signifying that the loop tends to amplify (“reinforce”) its effects and generate accelerating divergent behavior. In contrast, balancing (“B”) feedback loops tend to dampen changes and generate goal-seeking behavior. See Sterman (2000) for a more detailed description and analysis of causal loop diagrams and reinforcing and balancing loops.

The System Dynamics Model of Naval Fleet Parts Design and Manufacturing

The core of the system dynamics model structure is two aging chains, each a sequence of alternating stocks and the flows in which materials or information matures over time due to processes (Sterman, 2000). These aging chains reflect the sequential processes that add value to either information used to manufacture a part or the material that is used to manufacture the part. The information processing structure models the flow of the parts information through the processes identified by Kenney and the collection and processing of existing conditions information. More specifically, the model reflects receiving parts requests, processing parts requests, library searches, inspection failures, functional check failures, design, preparing manufacturing files, and “fixturing.” These information flows are typically constrained by the workforce applied to each process and the time required to process the information for an average part. However, the “Complete CAD design rate” is also constrained by the rate at which “Complete existing conditions surveys, etc.” occurs. Changing the information processing times is one of the impacts that different information technologies (i.e., 3DLST and CPLM) have on the model. See Ford and Housel (2014) for details.

In the system dynamics model, the information processes are separated by stocks, the accumulations of information that are waiting to be processed or that are being processed in backlogs and works-in-progress. These accumulations of net inflows and outflows create delays in systems, “remember” the net impact of past inflows and outflows, and provide momentum that can drive flows (Sterman, 2000). The dynamic movement of information through these accumulations is controlled directly by their inflows and outflows. Those inflows and outflows (i.e., the information processes) are controlled by many feedback loops. The movement of information through the basic processes identified by Kenney (2013) provided the basis for modeling the impacts of CPLM on parts replacement. In addition to the information processes identified by Kenney (2013), the information processing portion of the model reflects the collection of existing conditions information for use in parts manufacturing. This allows the explicit modeling of 3DLST, which can greatly improve this information process. The information processing structure also includes part of the two feedback structures created by the failure of parts to pass inspection or functional checks, as described in the results of data collection above. These feedback loops pass through the CAD design and manufacturing files processes, the parts manufacturing processes (described next), and back to the CAD design process when a part fails an inspection for functional test.

The manufacturing processing portion of the model structure depicts the flow of parts through the manufacturing processes. More specifically, the model reflects material acquisition, manufacturing, inspection, and functional checking. These flows are generally constrained by the workforce applied to each process and time required to perform the process on an average part for each process and by the fraction of parts that fail the inspection and functional tests. Changing these processing times and failure fractions, as suggested by the different technology strategies, are the primary means of reflecting the impacts of AM in the model. As in the information processes aging chain, the manufacturing processes are separated by stocks, the accumulation of parts that are waiting to be processed or that are being processed in backlogs and works-in-progress. The flows that link those stocks (i.e., the manufacturing processes) are controlled by feedback loops. As described above, the rate of inspection failure and functional check failure form a critical part of the feedback structure of the model by recycling work back into the information processes for correction before the manufacturing and testing processes can be repeated.

Model Testing

The model was tested using standard tests for system dynamics models (Sterman, 2000), including tests of structural validity and behavior validity. Structural validity was increased by basing the model structure on established information about the system being modeled and data collected directly from the system operators and managers. Unit consistency checks verified that the formal model conformed to system conditions. Model behavior tests included extreme conditions testing and behavior similarity testing. The model also created behavior patterns that are similar to those known or suspected to occur in the actual system. These and other tests indicate that the model is useful for simulating naval parts design and manufacturing for investigating the impacts of AM, 3DLST, and CPLM in ship maintenance processes. See Ford and Housel (2014) for details.

Although in the current work, the system dynamics model is used to generate input for the KVA model, in future work it can also be used to investigate reductions in parts manufacturing inventories and infrastructures with their related cost savings and the transitions from current practices to those in which new technologies have been adopted and become standard operating procedures.

Knowledge Value Added Models of Naval Fleet Parts Design and Manufacturing

The output (flow rates) from the system dynamics model were used to build KVA models of six scenarios that reflect different strategies for the adoption and use of the three technologies (3DLST, CPLM, and AM) in naval parts production for ship maintenance:

- **As-Is:** Current processes used at the depot where data was collected
- **To-Be#1:** Immature AM in which AM is used only to create prototypes
- **To-Be#2:** Immature AM with CPLM and AM being used only to create prototypes
- **To-Be#3:** Immature AM with 3DLST, CPLM, and AM being used only to create prototypes
- **Radical#1:** Mature AM with CPLM and AM being used to create both prototypes and final parts
- **Radical#2:** Mature AM with 3DLST, CPLM, and AM being used to create both prototypes and final parts

The scenarios differ in two dimensions: the technologies used, and the scale of the adoption and use of those technologies. In this way, the model results can be used to assess how these two important aspects of technology adoption impact costs.

Assumptions used in building the KVA models include the following:

- The use of 3DLST reduces the time required for gathering, preparation, and reporting of existing conditions on board the ship from 60 hours to 16 hours.
- The use of 3DLST reduces the number of persons required to collect existing conditions information and transform that into CAD for design by a factor of four.
- The use of 3DLST reduces inspection failure rates by 5% (from 20% to 15%).
- The use of AM reduces the time required to manufacture a part from an average of 40 hours to five hours, including set-up time.

- The use of immature AM reduces material waste in manufacturing by 40% (from 50% to 10%), and the use of mature AM reduces material waste in manufacturing by an additional 5% (from 10% to 5%).
- The use of AM increases throughput by a factor of 30. This is based on an expert interview that includes a description of an engineer being able to complete three to four iterations of a part per year with the current technologies and processes but being able to complete “hundreds” of iterations per year as envisioned (Draguicevich, personal communication, 2013). 100/4 = 25 times more throughput. 100/3 = 33 times more throughput. For the analysis, 30 times was assumed.
- The use of information technology in AM, CLMP, and 3DLST add new value to the processes that they impact, whereas the use of information technology in traditional technologies and processes primarily replace work that could be done by humans.
- A market comparable approach was used to estimate a surrogate revenue stream. The surrogate review stream was assumed to be the product of the unit market value of the product (from the data collected) and the volume of products generated in each scenario.

Results

Knowledge Value Added Model Simulations of Naval Fleet Parts Design and Manufacturing

The results of the KVA models of the six scenarios are shown in Tables 1–6.

Table 1. As-Is (Current Technologies) Scenario

AS IS - Current Technologies		
Processes	**Benefit: Cost Ratio**	**ROI (%)**
Process request	1.28	28%
Search Library	0.71	-29%
Prep CAD	5.75	475%
Fixturing	4.17	317%
Manufacture part	1.65	65%
Inspect part	1.56	56%
Check functionality	0.25	-75%
Totals:	**1.30**	**30%**

Table 2. To-Be#1 (Immature AM) Scenario

TO-BE#1- Immature AM		
Processes	**Benefit: Cost ratio**	**ROI (%)**
Process request	0.09	-91%
Search Library	0.14	-86%
Prepare CAD & Add manuf	2.25	125%
Fixturing	0.83	-17%
Manufacture part	0.32	-68%
Inspect part	0.61	-39%
Check functionality	0.05	-95%
Totals:	1.12	12%

Table 3. To-Be#2 (Immature AM + CPLM) Scenario

TO-BE#2- Immature AM + CPLM		
Processes	**Benefit: Cost ratio**	**ROI (%)**
Process request	0.67	-33%
Search Library	0.33	-67%
Prepare CAD & Add manuf	6.57	557%
Fixturing	2.22	122%
Manufacture part	0.77	-23%
Inspect part	1.54	54%
Check functionality	0.11	-89%
Totals:	1.92	92%

Table 4. To-Be#2 (Immature AM + CPLM + 3DLST) Scenario

TO BE#3-Immature AM + CPLM + 3DLST		
Processes	**Cost to Benefit Ratio**	**ROI (%)**
Process request	0.78	-22%
Search Library	0.47	-53%
Prepare CAD & Add manuf	4.00	300%
Fixturing	1.27	27%
Manufacture part	0.44	-56%
Inspect part	0.88	-12%
Check functionality	0.07	-93%
Totals:	1.40	40%

Table 5. Radical To-Be#1 (Mature AM + CPLM) Scenario

RADICAL TO-BE#1- Mature AM + CPLM		
Processes	**Benefit: Cost ratio**	**ROI (%)**
Process request	3.13	213%
Search Library	1.27	27%
Prepare CAD & Add Manuf	26.01	2501%
Inspect part	3.08	208%
Check functionality	0.48	-52%
Totals:	**8.87**	**787%**

Table 6. Radical To-Be#2 (Mature AM + CPLM + 3DLST) Scenario

RADICAL TO-BE#2-MatureAM+CPLM+3DLST		
Processes	**Cost to Benefit Ratio**	**ROI (%)**
Process request	36.35	3535%
Search Library	4.82	382%
Prepare CAD & Add Manuf	104.83	10383%
Inspect part	11.68	1068%
Check functionality	1.82	82%
Totals:	**14.91**	**1391%**

Estimates of Cost Savings

The KVA model results were used to estimate potential cost savings. The cost estimate of each of the six scenarios is the sum of four components, as shown in Table 7.

Table 7. The Four Components of Each Scenario Cost Estimate

	Prototype parts produced	**Final parts produced**
Old technologies	Prototype cost using old technologies	Final parts cost using old technologies
New technologies	Prototype cost using new technologies	Final parts cost using new technologies

The cost estimate for each cell in Table 7 was made on an annual basis using the specific benefits and ROI for the cell and the definition of ROI, as described below. Benefits were estimated using a surrogate revenue stream based on the market comparable value of the output that would be produced internally by the scenario. Each cell's surrogate revenue stream was the product of the annual production of prototype or final parts and the market comparable value of that type of part. Production rates were estimated based on information

from the interview with the expert (Draguicevich, personal communication, 2013), who suggested the following values for current operations (As-Is scenario):

- 2,000 prototypes per year using AM
- 3,000 prototypes each year using traditional methods
- 25,000 final parts, all using traditional methods

The market comparable value of an average prototype was also based on the interview of the expert who said, “Externally we see charges anywhere between $6,000 to $8,000 dollars and upwards of $15,000 per model” and later confirmed that $12,000 was “at the upper end of your range” (Draguicevich, personal communication, 2013). Based on this, the value of an average prototype was estimated to be the mean of $6,000 and $15,000 (= 10,500/prototype). The average value of a finished part was assumed to be four times that of a prototype, or $42,000 per final part. The products of the production rates and market comparable values were summed across part type and technologies to estimate the surrogate revenue for each scenario.

Table 8 shows the calculation of the costs using the As-Is scenario as an example calculation of a surrogate annual revenue for a scenario.

Table 8. Example Calculation of the Surrogate Revenue Streams for the Four-Part/Technology Types (As-Is Scenario)

	Prototypes			Final Parts		
	Production (parts/yr)	**Market comparable value** ($1,000/part)	**Surrogate revenue stream** ($1,000/yr)	**Production** (parts/yr)	**Market comparable value** ($1,000/part)	**Surrogate revenue stream** ($1,000/yr)
Old technologies	3,000	$10.5	**$31,500**	25,000	$42.0	**$1,050,000**
New technologies	2,000	$10.5	**$21,000**	0	$42.0	**$0**

The ROI values of each cell in Table 9 were derived from the KVA model results (see previous section), except for traditional processes without use of the three new technologies, for which inadequate data was available to build a KVA model. This return was estimated to be half of the ROI of the As-Is scenario (30%/2 = 15%) for all scenarios.

The benefits and ROI were combined to estimate scenario costs using the definition of return on investment:

$$\text{ROI} = (\text{Benefits} - \text{Costs}) / \text{Costs},$$

which can alternatively be written as

$$\text{Cost} = \text{Benefits} / (\text{ROI} + 1).$$

The results of applying the method above are shown in Table 9.

Table 9. Estimated Annual Parts Production Costs and Cost Savings

Scenario Simulation Name	Scenario Description	Old techn. prototypes / year	New techn. prototypes / year	Old techn. final parts / year	New techn. final parts / year	ROI - old techn.	ROI - new techn.	Prototype cost (X$1,000)	Final parts cost (X$1,000)	Total Cost (X$1,000)	Cost Savings from As-Is scenario (X$1,000)
As-Is	Current technologies	3,000	2,000	25,000	0	15%	30%	$43,469	$911,801	$955,270	**$0**
To-Be #1	Immature Additive Manufacturing	0	5,000	25,000	0	15%	12%	$46,716	$911,801	$958,516	**-$3,247**
To-Be #2	Immature Additive Manufacturing + CPLM	0	5,000	25,000	0	15%	92%	$27,379	$911,801	$939,180	**$16,090**
To-Be #3	Immature Additive Manufacturing + CPLM + 3DLST	0	5,000	25,000	0	15%	40%	$37,444	$911,801	$949,245	**$6,025**
Radical To-Be #1	Mature Additive Manufacturing + CPLM	0	5,000	0	25,000	15%	787%	$5,920	$118,392	$124,311	**$830,959**
Radical To-Be #2	Mature Additive Manufacturing + CPLM + 3DLST	0	5,000	0	25,000	15%	1391%	$3,520	$70,401	$73,922	**$881,348**

The results of the modeling (Table 9) show that substantial savings (up to $881 million) can be captured in naval parts production through the widespread adoption and mature use of AM, CPLM, and 3DLST. However, the adoption of new technologies does not generate savings under all conditions. For example, adopting only one new technology (AM) without the requisite supporting technologies (e.g., CPLM) at a small scale (prototypes only) can cost more than it saves (see $3,247,000 in the far right column and “To-Be#1” row in Table 9).

The estimated savings generated by different technologies and scaling choices in Table 9 were compared to better understand the impacts of adopting different technologies at different scales (see Table 10). For example, the $19 million/year savings from adding CPLM (see Table 10, column 3, row 3) can be estimated as the difference between the savings from the small scale use of AM and CPLM (see Table 10, column 1, row 3) and the savings from the small scale use of AM only (see Table 10, column 1, row 2).

Table 10. Estimated Annual Cost Savings of AM, CPLM, 3DLST, and Scaling Up Use

			1	2	3	4	5	
	Scenario Name	Scenario Description	Savings from As-is scenario (X$1,000)	Savings from Additive Manufacturing (X$1,000)	Savings from Collaborative Product Lifecycle Management (X$1,000)	Savings from 3D Laser Scanning Technology (X$1,000)	Savings from scaling up adoption and use (X$1,000)	Notes on savings by specific strategies
1	As-is	Current technologies	0					
2	To-Be#1	Immature Additive Manufacturing	-$3,247	-$3,247				←(To-Be#1)-(As-is) Small scale use
3	To-Be#2	Immature Additive Manufacturing + CPLM	$16,090		$19,337			←(To-Be#2)-(To-Be#1) Small scale use
4	To-Be#3	Immature Additive Manufacturing + CPLM + 3DLST	$6,025			-$10,065		←(To-Be#3)-(To-Be#2) Small scale use
5	Radical To-Be#1	Mature Additive Manufacturing + CPLM	$830,959				$814,868	←(Rad. To-Be#1)-(To-Be#2) Scale up to produce final parts
6	Radical To-Be#2	Mature Additive Manufacturing + CPLM + 3DLST	$881,348	(Rad. To-Be#2)-(Rad. To-Be#2) → Large scale use		$50,390	$875,323	← (Rad. To-Be#2)-(To-Be#3) Scale up to produce final parts

The results indicate that specific technologies can create different added costs or cost savings under different scaling assumptions. More specifically, if used on a small scale, AM alone costs $3 million/year over current technologies, but adopting AM and CPLM can save $16 million/year over As-Is processes ($19 million/year over AM alone). Similarly, adding 3DLST to small scale AM and CPLM costs $10 million/year (Table 10, column 4, row 4).

The larger cost differences are driven by the adoption and use of scaling in technologies decisions. First, all cost savings for large-scale adoption and use of multiple technologies are orders of magnitude larger than savings with small-scale adoption and use (see Table 10, column 1, rows 5 and 6 versus rows 2 through 4). Scaling up also greatly increases the impact of specific technologies. For example, scaling up AM and CPLM increases savings by $815 million (see Table 11, column 5, row 5) and increases the savings captured by AM, CPLM, and 3DLST by $875 million (see Table 10, column 5, row 6). Notice that scaling up adoption and mature use changes the impact of 3DLST alone from increasing costs by $10 million/year (see Table 10, column 4, row 4) to saving $50 million/year (see Table 10, column 4, row 6).

These results show the importance of scaling up the adoption and mature use of new technologies to capture large production savings. They also indicate that some technologies (e.g., 3DLST) may add value only if other technologies are in place (AM and CPLM) and widely used to make final parts as well as prototypes.

Conclusions

The cost savings estimates in this study were based on the actual use of new design and production technologies by the North Island NAVAIR maintenance depot to build two types of simulation models of ship maintenance. Given that the NAVAIR maintenance depot focused on the same kinds of legacy repair and replacement parts that are most prevalent in routine ship maintenance processes, extrapolating this actual experience with AM was appropriate for use in development of the models for the current study. The derived models were used to simulate six possible scenarios of technology adoption and use. The results were used to estimate design and production costs and thereby potential cost savings for each scenario that used the three new technologies. Comparison of potential cost savings

across the scenarios provided estimates of the cost savings by mature and immature use of the three technologies. Estimated impacts on annual production costs ranged from increasing costs by $3 million if AM alone is adopted on a small scale to saving over $875 million if AM, CPLM, and 3DLST are adopted and used to create both prototypes and final parts. Scaling up adoption and use, from existing ship maintenance processes to the widespread generation of prototypes and creation of final parts, were found to have more impact on costs than the selection of individual technologies alone.

The results of this study have several implications for naval fleet maintenance in terms of replacement-part production. First, the results reinforce previous studies in forecasting substantial benefits from using AM, CPLM, and 3DLST in ship maintenance processes. Beyond this, the current study results indicated that these technologies, when incorporated with AM, provide the best results when used together and when adopted on a large scale to capture more of the potential benefits.

Despite the very large cost reductions that are available through the adoption and use of the technologies studied here, all of those benefits are not available immediately. Time and significant effort are required to achieve mature use of the technologies by incorporating them and other potentially valuable technologies into the standard operating procedures of ship maintenance. Acquisition regulations (e.g., about outsourcing) will require changes to allow and facilitate the widespread use of these technologies. It appears likely that, with some relaxation in acquisition rules that make it difficult for Navy maintenance operations to do some of the manufacturing of legacy parts, the Navy will be able to hire more personnel to perform these duties and reduce costs substantially in spite of the increased personnel costs. This will require a new way of thinking about labor costs and overall costs in acquisitions and operations that currently are primarily focused on reducing head count. By focusing on the potential value that these three technologies add to ship maintenance processes, this study provides an alternative to head count reduction for reducing costs. These challenges will require a degree of patience on the part of leadership to obtain the very substantial cost savings possible when the use of these three technologies becomes a mature aspect of ship maintenance processes.

The current work also has implications for future research. The next steps in this line of research include investigating the impacts of these technologies on the outsourcing of fleet maintenance, estimating the impacts of these technologies on manufacturing infrastructures and material inventory costs, the continued documentation of the current use of these technologies within some Naval maintenance processes for ships and NAVAIR, and the investigation of costs and savings during adoption and scaling up. This study's results were purposefully conservative and based on only two levels of ship maintenance operations. Future research will need to estimate the total cost savings possible when the technologies become routine aspects of all Navy maintenance processes. The continued research of new technology adoption and use for naval fleet maintenance issues will accelerate an improved understanding of how advanced technologies can be effectively and efficiently adopted to generate enormous cost savings while improving fleet operational availability.

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